Environmental Pollution 288 (2021) 117799

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

Production and resource utilization of flue gas desulfurized gypsum in China - A review☆

Sen Liu [a,b], Wei Liu [a,b], Fen Jiao [a,b], Wenqing Qin [a,b], Congren Yang [a,b,*]

[a] School of Minerals Processing and Bioengineering, Central South University, Changsha, 410083, China
[b] Key Laboratory of Hunan Province for Clean and Efficient Utilization of Strategic Calcium-containing Mineral Resources, Central South University, Changsha, 410083, China

ARTICLE INFO

Keywords:
Flue gas desulfurization
FGD gypsum
Recycling
Sustainability

ABSTRACT

Flue gas desulfurized gypsum (FGD gypsum), mainly originates from thermal power plants, smelters, and large-scale enterprise boilers. This article reviews the production in China and the latest beneficial utilizations of FGD gypsum. China is a large coal-consuming country and has always had serious SO_2 emissions. Therefore, the Chinese government has implemented a large number of desulfurization measures since 2006. With continually increasing energy consumption and increasingly stringent environmental requirements, the production of FGD gypsum has exceeded 10^8 tons. The basic properties and the current beneficial applications of FGD gypsum are summarized here. The practical application of FGD gypsum in four fields—building materials, agriculture, material synthesis, and soil—and its impact on the environment, are analyzed. Finally, a new direction is proposed for the future utilization of FGD gypsum.

1. Introduction

Flue gas desulfurized gypsum mainly comes from thermal power plants, smelters, and large-enterprise boilers, and contains industrial by-products produced through a wet desulfurization combustion process, where SO_2 gas and lime slurry react under strong oxidation conditions. The main component of this gypsum is calcium sulfate dihydrate, which also contains calcium carbonate, calcium sulfite and other impurities (Koralegedara et al., 2019b). As the demand for environmental protection increases, the output of FGD gypsum has increased worldwide, especially in the European Union and China. At present, the main way to reuse FGD gypsum is t to use it as an auxiliary material for building materials, almost without any intermediate process (Pedreno-Rojas et al., 2020). This is also the main method of utilization in countries and regions with large stockpiles such as China, the European Union, and Japan (Pantini et al., 2019). But this will lose a certain amount of precious resources, and there may be higher sulfate, hydrogen sulfide and greenhouse gas emissions during the treatment process (Jimenez-Rivero and Garcia-Navarro, 2016, 2017b). Adding FGD gypsum will reduce the quality of building materials, so the maximum amount will be limited and cannot be used in large quantities, which will lead to stockpiling (Cordon et al., 2019; Jimenez-Rivero and Garcia-Navarro, 2017a). Therefore, the use of FGD gypsum is very extensive, in order to increase the potential use value, especially in the fields of construction materials, agriculture, material synthesis, and soil.

The main utilization method of FGD gypsum is still used in construction materials (Ye et al., 2019). As an auxiliary material or instead of natural gypsum, it can be widely used in concrete, walls, concrete, etc. It is the best way to use desulfurized gypsum in large quantities, but its economic value is relatively low (Pedreno-Rojas et al., 2020). Secondly, it can be used in agriculture and soil as a source of high-quality sulfur and calcium resources. Many scholars have evaluated its feasibility, which is beneficial to increase plant yield (Tao et al., 2019) and improve soil salinity (Wang et al., 2021). However, since FGD gypsum itself has certain heavy metals, there may be safety problems of heavy metals flowing into the ecosystem during the utilization process (Fu et al., 2019). The requirements for the composition of FGD gypsum are relatively strict, and the scale of utilization is subject to certain restrictions. In addition, the use of FGD gypsum to synthesize high value-added materials is also one of the current research hotspots. The main synthetic materials are α-hemihydrate gypsum dihydrate, calcium carbonate, adsorption materials and composite material (Wang et al., 2019;

☆ This paper has been recommended for acceptance by Dr SU SHIUNG LAM.

* Corresponding author. School of Minerals Processing and Bioengineering, Central South University, Changsha, 410083, China.
E-mail address: yangcongren@csu.edu.cn (C. Yang).

https://doi.org/10.1016/j.envpol.2021.117799
Received 16 May 2021; Received in revised form 2 July 2021; Accepted 15 July 2021
Available online 17 July 2021
0269-7491/© 2021 Elsevier Ltd. All rights reserved.

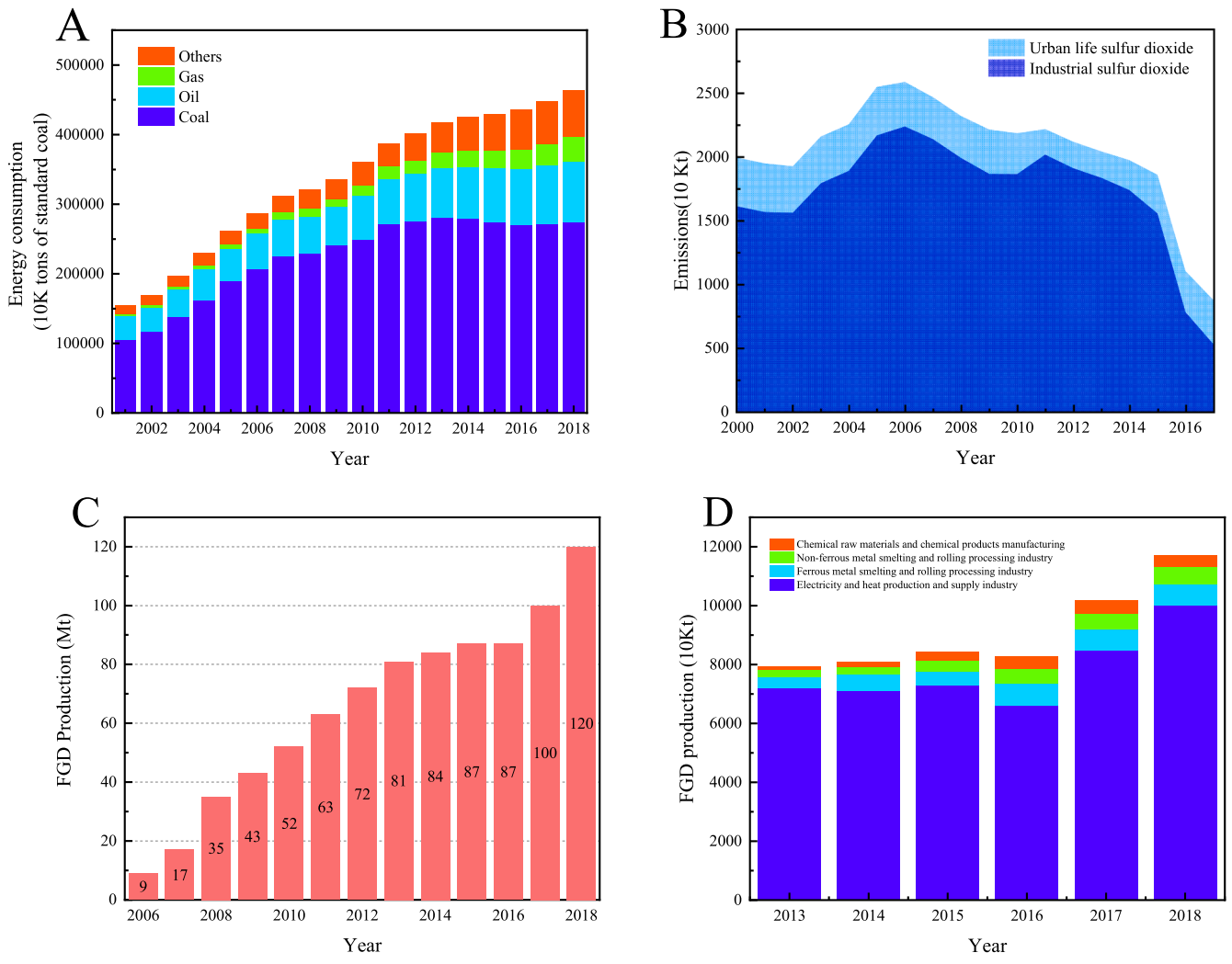

Fig. 1. Chinese energy consumption (A), sulfur dioxide emissions (B), China's FGD production (C) and industry distribution (D). The data were obtained from the MEE.

Wang, T. et al., 2020; Yang et al., 2019). Synthetic materials are an effective way to realize the high-value utilization of FGD gypsum. However, most of them are on a laboratory scale, and industrial production is relatively small, so large-scale utilization of desulfurized gypsum cannot be realized.

As the world's largest producer of FGD gypsum, China occupies a very prominent position in the world, and its utilization is also imminent. This article reviews the production and development of China's FGD gypsum in the past 20 years, and determines its production process, composition, and environmental impact. The current beneficial utilization and latest research of FGD gypsum are summarized, and its utilization methods, principles, feasibility, environmental impact, and application prospects are analyzed. Finally, a possible closed-loop utilization of FGD gypsum is proposed, for the future.

2. Characteristics of FGD gypsum produced in China

2.1. Production of FGD gypsum

It is estimated that by 2020, China will emit more than 10^8 tons of FGD gypsum every year. At present, due to the high decomposition temperature and complex composition of gypsum, only a small part of FGD gypsum is recycled; most of it is directly stored as solid waste. This not only causes serious pollution to the environment, but also wastes calcium and sulfur resources.

As China is rich in coal resources, coal has always occupied a dominant position in the country's energy structure (Li et al., 2018). About half of the total amount of coal consumed is used for power generation. In recent years, China has been continually improving its energy structure and has focused on the development of green and renewable energy, but coal is still the main energy source (Fig. 1A). Due to the high sulfur content of coal in China, the coal combustion process emits a large amount of sulfur dioxide into the atmosphere. Sulfur dioxide has adverse effects on human health and causes environmental pollution. In the past 20 years, China's economy has been developing rapidly and its industrial level has been increasing, almost day by day. At the same time, sulfur dioxide pollution has become more and more serious (MEE, 2000–2019). Sulfur dioxide emissions from industrial production processes are the main source of sulfur dioxide pollution (Fig. 1B). In order to control the increasingly serious air pollution and reduce the environmental damage caused by SO_2 pollution and its adverse impacts on social and economic development, the Chinese government first proposed a total sulfur dioxide reduction target in 2006 to reduce sulfur dioxide emissions. Since 2000, China has taken many desulfurization measures (Table S1), causing the production of flue gas-generated desulfurized gypsum to continue to rise (MEE, 2000–2019).

Thus, since 2006, more and more FGD gypsum has been produced and accumulated, in China (Fig. 1C). Consequently, the combustion carried out in thermal power plants, smelters, and large-enterprise

boilers are producing a large amount of gaseous sulfur dioxide. With the rise of environmental protection awareness, the control of sulfur dioxide emissions from these enterprises is becoming more and more stringent. The output of flue gas desulfurized gypsum is growing rapidly, especially in the electricity and heat production and supply industry (Fig. 1D). In 2014, it became one of China's bulk solid wastes (solid waste with an annual output of more than 10 million tons in production activities in various industrial fields, which has a great impact on the environment and safety) (MEE, 2014–2019).

2.2. Desulfurization process

Three desulfurization methods are commonly used: dry desulfurization, semi-dry desulfurization and wet desulfurization (Michalski, 2017). Dry flue gas desulfurization (Klaka et al., 2018) refers to the application of powder and granular absorbents to react with sulfur dioxide under dry conditions, and the reaction products are also in a dry state. The desulfurized flue gas is discharged after being dedusted by a dust collector. Dry desulfurization has the advantages of not scaling or corroding equipment, producing no waste water, and having low energy consumption. The flow of the dry desulfurization process is simple, and the desulfurization efficiency is over 85%.

Semi-dry desulfurization reaction is carried out via gas, solid and liquid phases (Katolicky and Jicha, 2013). The heat of the flue gas is used to evaporate and absorb the moisture in the liquid. While drying, the sulfur dioxide in the flue gas reacts with lime to form calcium sulfite, and the final product is dry and powdery. The semi-dry method does not produce waste water, and the reactants can be comprehensively utilized, with low investment and operating costs. Semi-dry desulfurization methods include the spray drying method and the flue gas circulating fluidized bed method.

Wet desulfurization mainly uses a wet desulfurizer to desulfurize the flue gas in the desulfurization device behind the flue gas dust removal system, removing the sulfur dioxide in the flue gas (Xie et al., 2012). This method is the most used desulfurization method because of its high desulfurization efficiency (90%–98%), large capacity, low cost, and easy recovery of by-products. The main methods are the wet limestone-gypsum method, the magnesium oxide method, sea-water desulfurization, and the double alkali method. The two most common wet desulfurization processes are the limestone/lime-gypsum wet FGD process and the flue gas circulating fluidized bed desulfurization process (Fig. 2).

The main desulfurization agent is a calcium-sourced desulfurization agent (limestone, lime, and calcium carbide slag). The main reaction consists of four steps, as follows:

① The dissolution of calcium-based substances produces Ca^{2+}
② SO_2 absorption/neutralization

$$SO_2+H_2O = 2H^{+}+SO_3^{2-}$$
$$Ca^{2+}+SO_3^{2-} = CaSO_3$$

③ Forced oxidation

$$1/2O_2+CaSO_3 \rightleftharpoons CaSO_4$$

④ Crystal

$$1/2H_2O + CaSO_3 = CaSO_3\cdot 1/2H_2O$$
$$2H_2O + CaSO_4 = CaSO_4\cdot 2H_2O$$

2.3. Composition of FGD gypsum

The properties and textures of FGD gypsum and natural gypsum are similar. They have the same mineral phase and transformation form, and the chemical composition is calcium sulfate dihydrate ($CaSO_4\cdot 2H_2O$), which is non-radioactive, with a particle size of 5–50 μm, and the crystals are mainly rhomboid (Koukouzas and Vasilatos, 2008). The appearance of FGD gypsum shows generally loose particles with a large moisture content (10%–20%) (Jiang et al., 2019). In most cases, the color of FGD gypsum is primarily white or slightly yellow, but if some impurities such as fly ash are mixed in during the desulfurization process, the gypsum will turn black. The purity of most FGD gypsum in China is 75%～90%, and the purity of the product paste in eastern developed areas of China can reach more than 90% (He and Li, 2019). The composition of FGD gypsum can be seen in Table 1.

In a strong oxidizing atmosphere, gypsum is mainly calcium sulfate dihydrate, but if the oxidizing atmosphere is insufficient, some calcium sulfite hemihydrate will be formed. Unreacted calcium hydroxide and calcium carbonate may also be present. Lancia and Musmarra studied the oxidation rate kinetics of calcium sulfite, and Liu et al. supplemented them. They all found the same reaction mechanism of parallel reaction rates (Lancia and Musmarra, 1999; Liu et al., 2001).

2.4. Environmental risks of FGD gypsum

A large amount of FGD gypsum will not only waste land resources, but also contain many heavy metal elements, which will flow into the natural environment under rain, surface water, etc., causing serious environmental pollution. Desulfurization process is easy to capture volatile (As, Cd, Pb, Cu, Zn, etc.) and very volatile elements (Hg, S, Se, etc.), generally 1.26–4.33% of the total (Vejahati et al., 2010). Therefore, FGD gypsum contains a variety of metals (such as Cr, Cd, Cu, Zn, As, Hg, etc.), which are potentially dangerous to the environment. Furthermore, different sources of FGD gypsum contain different types of heavy metals, and the relative content of them varies greatly. For example, the Cr in the FGD gypsum accounts for about 46.8–56.1% of the total metal, which mainly exists in the form of solid oxides after condensation and chromates formed with gypsum; Zn accounts for about 25–46.7%, and Pb accounts for about 21.2–38.8%, both of which exist mainly in acid-soluble and reduced forms; Cu accounts for about 38.2–51.7%, mainly in the reduced form Zhao et al., 2018. These are the main metals in FGD gypsum, and if they are not well managed, they will cause certain risks (Hao et al., 2017). The heavy metals (HMs) in all FGD gypsum present a medium to high risk to the ecosystem (Fu et al., 2019; Zhao et al., 2017). The content of other metals is lower, but they may also have certain risks. For example, the average percentage of Hg leached is about 3% of the total Hg. But despite this small percentage, the potential leaching amount of mercury in FGD gypsum is about 0.65 tons per year (Hao et al., 2016). During the volatilization of As metal, ~50% of As will remain in the desulfurization residue and exist in the form of amorphous Fe-Mn oxide (Al-Abed et al., 2008). Some scholars have also found that aqueous complexes such as UO_2SO_4, H_2Se and $HAsO_2$ are formed in FGD gypsum under acidic conditions (Cordoba et al., 2015).

Metal pollution poses a threat to the ecological environment and public health. In order to eliminate the effects of different compositions of desulfurized gypsum, many scholars have studied methods of removing the harmful elements. At present, the more commonly used method for removing heavy metals is precipitation. By adding different precipitating agents, heavy metals such as mercury are removed in the form of precipitation (Sun et al., 2012; Zou et al., 2016). Conditions such as temperature and ultraviolet radiation are conducive to the release of mercury in FGD gypsum (Diao et al., 2018; Zhu et al., 2017). Through the ammonia (amine) solution, the heavy metals are formed into complexes, and the heavy metals from FGD gypsum are removed (Tan et al., 2017). In addition, some scholars have studied the method of mixing stabilizers into flue gas desulfurization gypsum before treating flue gas to minimize the risk of harmful substances in the leachate (Alvarez-Ayuso et al., 2008). Regarding heavy metals in FGD gypsum, many studies have shown that although the application of heavy metals has few adverse effects on the environment, the hazards of heavy metals

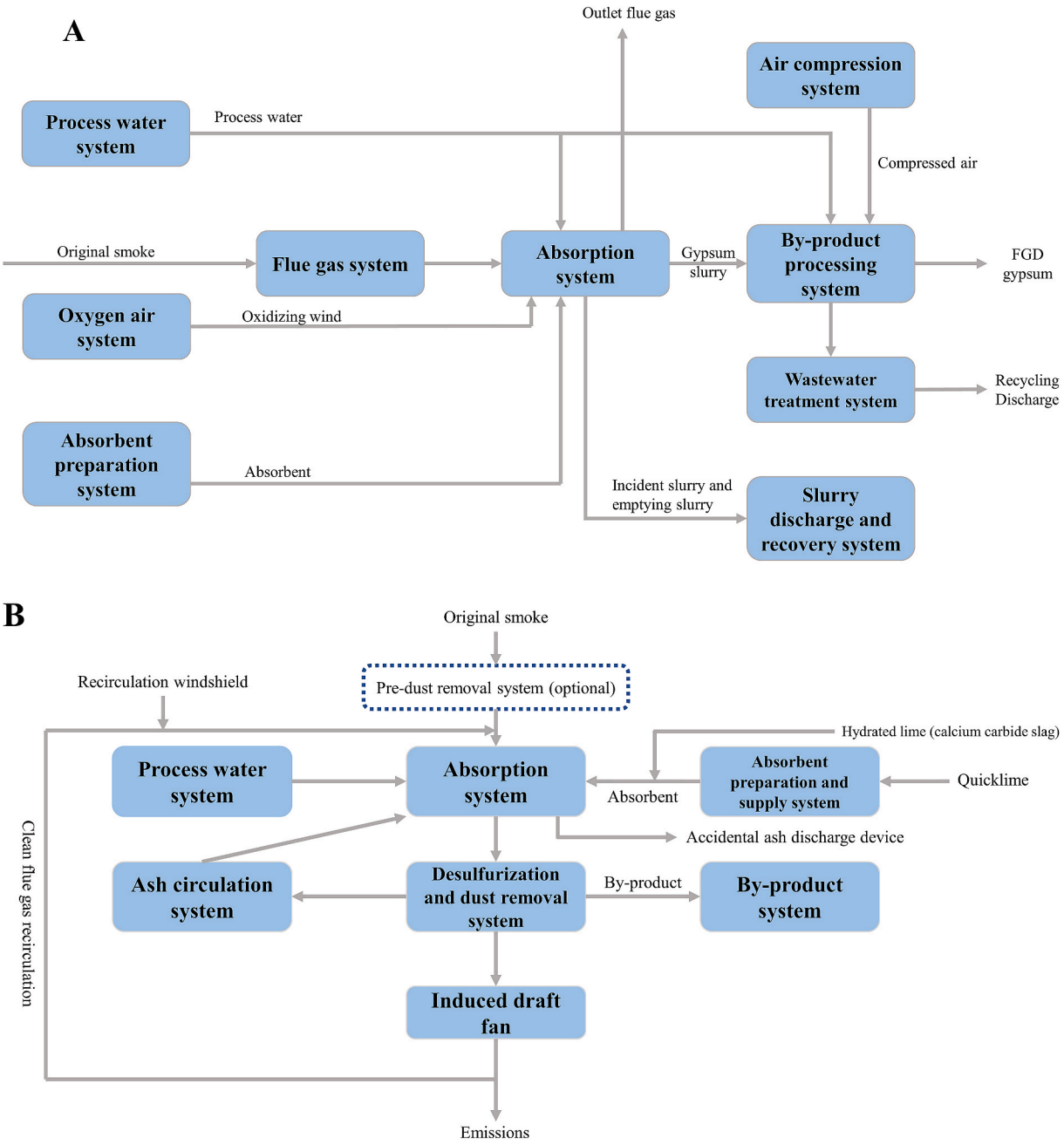

Fig. 2. Schematic diagram of limestone/lime-gypsum wet FGD process (A) and flue gas circulating fluidized bed desulfurization process (B).

Table 1
Composition of FGD gypsum.

Main element[a]	Concentration	Heavy metal elements[b]	Mean	Range
	%		mg/kg	mg/kg
O	46–46.7	Zn	63.5	40–96
Ca	25.5–30.4	Cr	38	12–58
S	17.3–19.9	Cd	0.7	0–1.6
C	2.9–4.0	Pb	4.7	0–13.3
Si	0.6–2.4	Ni	10.4	0.7–31.7
		Mn	24	2.1–56.1
		As	1.93	1.04–2.87
		Hg	0.891	0–4.33

[a] Source:.(Hao et al., 2017).
[b] Source: (Hao et al., 2016; Zhao et al., 2018).

should nevertheless be fully considered and studied.

3. Recycling of FGD gypsum

With the intensification of research, the advancement of technology and the improvement of comprehensive utilization levels in recent years, currently FGD gypsum is mainly used in the following applications.

3.1. Application of FGD gypsum in building materials

The main application field of FGD gypsum is building materials. FGD gypsum, as the origin of building materials, has the characteristics of low energy consumption, no waste residue and waste water discharge, recyclability, and fast production rate. It has different advantages when used in different building materials, as shown in Fig. 3 and Table 2.

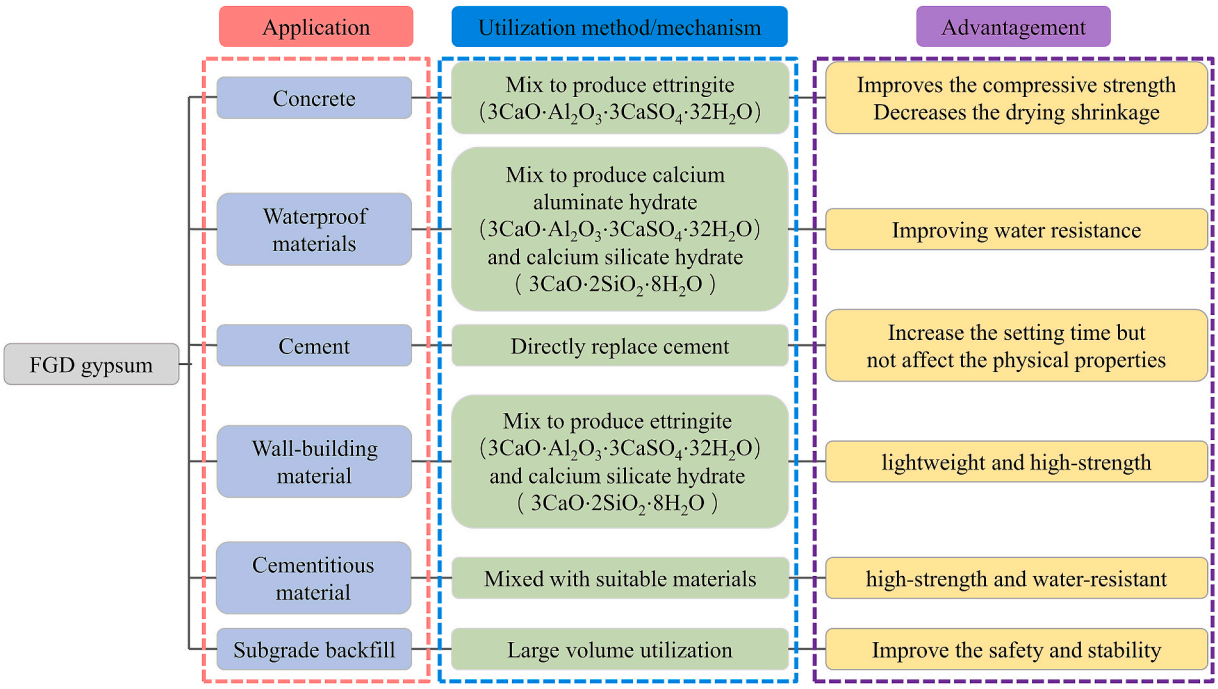
Application
Utilization method/mechanism
Advantagement
FGD gypsum
Concrete
Waterproof materials
Cement
Wall-building material
Cementitious material
Subgrade backfill
Mix to produce ettringite (3CaO·Al2O3·3CaSO4·32H2O)
Mix to produce calcium aluminate hydrate (3CaO·Al2O3·3CaSO4·32H2O) and calcium silicate hydrate (3CaO·2SiO2·8H2O)
Directly replace cement
Mix to produce ettringite (3CaO·Al2O3·3CaSO4·32H2O) and calcium silicate hydrate (3CaO·2SiO2·8H2O)
Mixed with suitable materials
Large volume utilization
Improves the compressive strength Decreases the drying shrinkage
Improving water resistance
Increase the setting time but not affect the physical properties
lightweight and high-strength
high-strength and water-resistant
Improve the safety and stability

Fig. 3. The utilization of FGD gypsum in different building materials.

3.1.1. Concrete

Adding FGD gypsum increases the compressive strength and reduces the drying shrinkage of concrete. Therefore, FGD gypsum is widely used in concrete materials. It strongly promotes the formation of ettringite (AFt), and forms a dense microstructure, which improves the compressive strength and decreases the drying shrinkage (Jiang et al., 2018). FGD gypsum can also be used in combination with other solid waste such as construction waste, tailings, smelting waste, agricultural waste, etc., providing higher synergistic benefits than solid waste alone (Phutthimethakul et al., 2020; Yu et al., 2016).

3.1.2. Waterproof materials

In order to develop and expand the application range of FGD gypsum, many studies have focused on overcoming its water resistance problem. After some types of pre-treatments, FGD gypsum can be made into a block, improving its water-resistance capabilities. For example, the combination of silicate clinker and FGD gypsum can improve its mechanical strength and water resistance by forming calcium aluminate hydrate and ettringite (Wu, Q.S. et al., 2019). Zhao et al. produced a waterproofing agent that can be mixed with calcined FGD gypsum to produce waterproof blocks (Zhao et al., 2012). Wansom et al. calcined FGD gypsum into flue gas desulfurized plaster, mixed it with fly ash and ordinary Portland cement to expand its applicability, improving its water resistance and compressive strength and minimizing the risk of sulfate attack under wet conditions (Wansom et al., 2019). Utilizing the excellent water performance of FGD gypsum, it is used as a waterproof dephosphorized tile material. After applying FGD gypsum, the total phosphorous concentration on the surface of the tiles is significantly reduced (King et al., 2016).

3.1.3. Cement

In cement applications, FGD gypsum can be used as a retarder in cement production. FGD gypsum has a low impurity concentration and is a suitable substitute for natural gypsum, since the physicochemical and morphological characterization results of FGD gypsum all show great similarity to natural gypsum, albeit with some drawbacks: the setting time is increased by about 1 h, and its compressive strength depends on the composition of the mixture (Caillahua and Moura, 2018). The crystal phase and microstructure analysis results of cement prepared with FGD gypsum showed that the hydration product of the prepared cement is similar to that of ordinary Portland cement and will not affect the physical properties of the cement (Seo et al., 2016). Meanwhile, the mixture of sulfate-containing materials and gypsum only affects the setting time (Tzouvalas et al., 2004). The hydration of calcium sulfoaluminate cement mainly depends on the amount of FGD gypsum and curing temperature. In the process, more ettringite and aluminum hydroxide are produced, thereby increasing the strength (Xu et al., 2017). Blending in FGD gypsum promotes the hydration of calcium aluminate cement (CAC), thereby rapidly forming ettringite (Guan et al., 2009). It is feasible to prepare sulphoaluminate cement from red mud produced by FGD gypsum and alumina; the cement clinker showed excellent mechanical strength (Wang, W.L. et al., 2013). FGD gypsum can also be used to make sulfuric acid and co-produce cement; FGD gypsum can supply all the CaO and SO_3 required in the cement. The optimal reduction temperature is 1270–1310 °C, and the appropriate time is 60–100 min. The main reaction is as follows:

$$2CaSO_4+C \rightarrow 2CaO+2SO_2\uparrow+CO_2\uparrow$$

$$Fe_2O_3+2Al_2O_3+2SiO_2+12CaO \rightarrow 2CaO\cdot SiO_2+3CaO\cdot SiO_2 +4CaO\cdot Al_2O_3\cdot Fe_2O_3+3CaO\cdot Al_2O_3$$

$$2SO_2+O_2 \rightarrow 2SO_3$$

$$SO_3+H_2O \rightarrow H_2SO_4$$

This method uses calcium and sulfur and has no by-products. However, due to the unstable composition of FGD gypsum, the process conditions are difficult to control and stabilize, the project investment is large, and the production equipment efficiency is low, limiting the promotion of this technology (Wu, S. et al., 2019).

3.1.4. Wall-building material

FGD gypsum has the characteristics of low energy consumption, recyclability, a rapid production rate and no waste residue or waste water, making it very useful as a wall-building material. The synergy among FGD gypsum cement-based composite materials improved the performance of these materials, which led to the formation of hydrated calcium silicate (CSH) and ettringite. This work proved the feasibility of preparing wall-building materials from FGD gypsum (Yang et al., 2020). Compared with an unfilled sample, the peak load of wall filled with FGD

Table 2
Representative application of FGD gypsum in building materials.

Application	Utilization method	Advantagement	References
Concrete	added 5% FGD gypsum as slag activation agent	CO_2 intensity of concrete production is reduced by 55%; compressive strength was 55.1 MPa	Jiang et al. (2018)
	5.5 wt% of FGD gypsum replaces cement	compressive strength was 45.18 MPa	Phutthimethakul et al. (2020)
	75% FGD gypsum with river sand and water	the 7-day compressive strength was up to 34 MPa	Yu et al. (2016)
Waterproof materials	6% silicate clinker modified FGD gypsum	the dry flexural strength and compressive strength were 5.4 MPa and 10.7 MPa, water absorption 28.5%	(Wu, Q.S. et al., 2019)
	used calcined FGD gypsum with the modifier (granulated blast-furnace slag and high calcium fly ash)	compressive strength exceeds 12.5 MPa; the softening and thermal conductivity coefficient were 0.84 and 0.15	Zhao et al. (2012)
	FGD gypsum: fly ash: cement = 20:40:40	the compressive strength was 59 MPa	Wansom et al. (2019)
Cement	2.1% of FGD gypsum and 1.4% of natural gypsum	the setting time increased ~1 h; compressive strength was ~50 MPa	Caillahua and Moura (2018)
	5% of FGD gypsum	compressive strength was 56.4–58.0 MPa	Seo et al. (2016)
	3.5% of FGD gypsum	compressive strength exceeds 50 MPa , the setting time is increased by about 1 h	Tzouvalas et al. (2004)
	Clinker: FGD gypsum = 80: 20	compressive strength was 40 MPa (curing temperature 40 °C)	Xu et al. (2017)
	FGD gypsum: red mud: bauxite: limestone = 15.18: 55.67: 11.14: 18.01, calcination at about 1300 °C	compressive strength was 61.3 MPa	(Wang, W.L. et al., 2013)
Wall-building material	the FGD gypsum mixtures (containing 6 wt % cement, 8 wt% fly ash, and 6 wt% silica fume)	dry compressive strength was 24.67 MPa; compressive softening coefficient 0.632; water absorption 17.6%	Yang et al. (2020)
	infilled lightweight FGD	the shear capacity of specimen was 24.97 kN/m	Wu et al. (2018a)
	100% FGD gypsum	compressive strength was 12.6 MPa, the flexural strength 4 MPa, energy absorbed 484 J/g	(Li, J. et al., 2015)
Cementitious material	20% FGD gypsum, 20% ground granulated blast furnace slag and 60% fly ash	compressive and flexural strength were 22.6 and 4.3 MPa	Zhao et al. (2012)
	adjust the ratio of SiO_2:Al_2O_3 in 800 °C thermally activated FGD gypsum/40 °C dried FGD gypsum	compressive strength of 800 °C/40 °C were 55 and 30 MPa	(Zhang, Y.J. et al., 2016)
	and metakaolin to 1:1		
	45% FGD gypsum, 50% ground blast furnace slag and 5% ordinary cement	compressive strength was 31.9 MPa	Pang et al. (2020)
Subgrade backfill	the ratio of FGD gypsum to slaked lime was 3 to 1, the dosage of water glass was 10%	7 days compressive strength was 1.625 MPa	Hua et al. (2010)
	1% NaOH-activated mixture (50% FGD gypsum and 50% waste fly ash)	bearing capacity and the ratio of compression modulus at 7 days were 320 kPa and 0.78	Ma et al. (2020)

gypsum increased by 1.72–2.54 times (Wu et al., 2018a; Wu et al., 2018b). Li especially emphasized the use of FGD gypsum to make refractory panels. The material has been widely used as a building insulation material, with low cost and environmental protection. Pure FGD gypsum panels have the best insulation capacity (52 min), much higher than pure gypsum panels (42.8 min) (Li, J. et al., 2015). Since wet FGD scrubbers can easily capture hazardous elements such as Hg and Cl (Lee et al., 2009; Liu et al., 2013), they may interact with wallboard. Therefore, in the production process of desulfurized gypsum wallboard, attention should be paid to the release of trace elements and their impact on the environment.

3.1.5. Cementitious material

FGD gypsum can be mixed with suitable materials such as fly ash, cement, slag, sol, etc., and the excitation between these materials can then facilitate the formation of high-strength hybrid cementing materials that are water-resistant and have other excellent performance characteristics (Wang, T. et al., 2020). Many scholars have done a lot of research in this area. For example, Zhong developed a series of new mortars using the uncalcined FGD gypsum (Zhong et al., 2012). Zhang et al. used FGD gypsum (activated at 800 °C) as hydraulic supplementary cementing components (Zhang, Y.J. et al., 2016). Pang et al. experimented with a new type of FGD gypsum-based cementitious material (Pang et al., 2020). These cementitious materials all show good strength effects, as shown in Table 2.

3.1.6. Subgrade backfill

Because FGD gypsum is an unsatisfactory substitute for fly ash, steel slag or other by-products as a roadbed material, it has generally been regarded as waste to be landfilled. Other materials, however, have been proved satisfactory as mixers for FGD gypsum, to produce roadbed material. Using water glass and slaked lime to activate FGD gypsum can be used as a semi-rigid roadbed. This roadbed material has excellent mechanical properties and robustness (Hua et al., 2010). The NaOH-activated mixture (50% FGD gypsum and 50% waste fly ash) can also obtain acceptable mechanical properties for backfill applications (Ma et al., 2020). Even when FGD gypsum is landfilled, it can improve the safety and stability of the landfill (Alvarez-Ayuso and Querol, 2007).

3.1.7. Other building materials

With the continuing social and economic progress of developing countries, the demand for gypsum building materials continues to increase. The application of FGD gypsum in the building materials industry can not only effectively solve the problem of long-term large-scale storage, but also meet the needs of the building materials market.

The main research direction in this area is to improve the performance of building materials by adding FGD gypsum. It is completely feasible to directly replace natural gypsum in building materials with FGD gypsum. It was observed that whether calcium sulfate was produced by FGD or by natural gypsum, ettringite was still formed by the hydration of alumina, and when calcium hydroxide was added as well, CSH was formed by the hydration of silica (Telesca et al., 2013). FGD gypsum can also be used directly to prepare ultra-high-strength building materials, which has excellent mechanical properties and also performs well in terms of water and frost resistance (Lei et al., 2017). The FGD gypsum can be made into gypsum board samples after pre-cleaning and using curing regulators. Compared with natural gypsum, cured gypsum obtained from FGD gypsum was found to have higher strength (Prakaypun and Jinawath, 2003). The semi-dry FGD gypsum is mixed with semi-hydrated gypsum and the inferior desulfurization ash is used as a building material. The mixed building materials can still meet the strength standard when added at 24% (Li, H.X. et al., 2019). FGD gypsum has an activation function when used as a building material. FGD gypsum can be used as a calcium sulfate source to activate other building materials, thereby improving the performance (Han et al., 2019).

3.2. Applications of FGD gypsum in agriculture

3.2.1. Plants

FGD gypsum contains calcium and sulfur resources, and many scholars regard it as a viable source of sulfur and calcium for agriculture (Table 3); it can actually increase plant yields. FGD gypsum created as a by-product of coal combustion may be a viable source of sulfur for canola grown in arid lands. Assessing the potential of using FGD gypsum as a source of sulfur fertilizer, it has been found that both FGD gypsum and ammonium sulfate provide sufficient amounts of sulfur for plants. The production of canola oil varies greatly depending on whether it receives sufficient sulfur, but the source of the sulfur is irrelevant. In general, adding FGD gypsum has no negative impact on soil quality (Desutter et al., 2011). A large amount of FGD gypsum is required to promote plant growth, although desulfurized flue gas with high boron and low levels of $CaSO_3$ is harmful to plant growth. Overall, FGD gypsum improved the growth response of forage plants grown in sterile low-pH soils (Clark and Baligar, 2003). In coastal saline-alkali land, the incorporation of FGD-gypsum increased the organic matter of soil layer. The addition of FGD gypsum further improved the soil properties and crop growth, possibly by accelerating the reclamation process of coastal saline-alkali land (Tao et al., 2019). FGD gypsum has a good improvement effect on soil sodium and acid. Adding FGD gypsum in the process of soil restoration will have a positive effect on plant growth (DeSutter et al., 2014). Many scholars have studied the effects of FGD gypsum on the growth of different plant crops. The combined application of FGD gypsum can significantly reduce soil salinity and increased sunflower yields by 17.4% and 20.4% in 2015 and 2016, respectively (Zhao et al., 2019a). Chen used FGD products or gypsum for growing alfalfa and soybeans, and found that it had a positive effect on alfalfa, but only a slight improvement of soybean harvest (Chen et al., 2005). Nan studied the effect of FGD gypsum and humic acid on the improvement of coastal saline soil and its influence on canola yield, and found that canola yield increased as the sodium adsorption rate decreased (Nan et al., 2016b). Codling used FGD gypsum as a calcium source for peanuts. The micronutrients in corn kernels fertilized by FGD gypsum were similar to those from superphosphate, indicating that FGD gypsum can be used as a calcium source for peanuts (Codling et al., 2015). FGD gypsum has also been proven to retain water and effectively improve water use, thereby increasing the profit margins of producers (Truman et al., 2010).

Table 3
Representative application of desulfurized gypsum in agriculture.

Application	Utilization method	Advantagement	References
Plant	FGD gypsum (0.75 t ha^{-1})	sunflower production increased by 17.4% in 2015 and 20.4% in 2016.	Zhao et al. (2019a)
	FGD gypsum (67 kg S ha^{-1})	Alfalfa production increased by 20–40%; soybean production increased by 5–10%	Chen et al. (2005)
	25% and 50% FGD gypsum	improved the rapeseed yield (increased by 11.20 and 14.92% in 25% and 50%)	Nan et al. (2016b)
	used FGD gypsum as a calcium source for peanuts	small differences in yield and Ca uptake	Codling et al. (2015)
Poultry and compost	5% biochar and 5% FGD gypsum	ammonia volatilization reduced by 26–59%; nitrate accumulation increased by 6.7–7.9 times	Febrisiantosa et al. (2018)
	10% FGD gypsum	the N loss were 10.8%	Guo et al. (2016)
	FGD gypsum (9.0 Mg ha^{-1})	reduce the load of Salmonella and fecal indicator bacteria *E. coli*	Jenkins et al. (2014)
	FGD gypsum (8.9 Mg ha^{-1})	total phosphorus concentration decreased from 22.13a to 7.81 b mg/L	Watts and Torbert (2017)

3.2.2. Poultry and compost

The research on poultry has focused mainly on the composting capacity of poultry and livestock manure (reducing air pollution and improving nutrients). FGD gypsum in the composting process of livestock manure could reduce ammonia volatilization, reduce total nitrogen loss, and increase nitrate accumulation (Febrisiantosa et al., 2018; Guo et al., 2016; Zhao et al., 2017). The application of FGD gypsum in agriculture can increase water penetration, reduce soil erosion, and reduce nutrient loss caused by the application of animal manure. It can also reduce the load of some flora (Jenkins et al., 2014). Some scholars also found that FGD gypsum and animal manure can be used together as fertilizer to reduce total phosphorus loss and other nutrient losses (Endale et al., 2014; Schomberg et al., 2018; Watts and Torbert, 2017). Previous studies have shown that adding FGD gypsum to poultry litter will reduce the total P and inorganic P in the H_2O component, and increase the two P forms in the $NaHCO_3$ component, while stacking poultry litter may increase the content of unstable phosphorus (Mishra et al., 2012). Treating the liquid fertilizer in a sedimentation tank with FGD gypsum before field application is particularly useful for farms applying surface fertilizers. It can reduce the potential loss of phosphorus after fertilizer application, thereby reducing the risk of eutrophication in waterways (Michalovicz et al., 2017).

Despite these benefits, there has been some concern about possible environmental contamination. Torbert studied the effects of applying FGD gypsum both alone and in combination with poultry litter on the soil, and analyzed the different elements content in plants, soil, and runoff samples. The results showed that the FGD gypsum did not cause any increase of potentially toxic elements. In fact, FGD gypsum can reduce the concentration of some elements such as P, As, and Fe (Torbert et al., 2018; Zhai et al., 2020).

3.3. Application of FGD gypsum in synthetic materials

3.3.1. Alpha-hemihydrate gypsum

The main synthetic materials are α-hemihydrate gypsum dihydrate, calcium carbonate, adsorption materials and composite material (Table 4). The preparation of α-hemihydrate gypsum (α-HH) is an effective way to realize the high-value utilization of FGD gypsum. The formation mechanism and crystal structure of α-HH are shown in Fig. 4. FGD gypsum is the main object to replace analytical grade calcium sulfate dihydrate to prepare α-HH.

Table 4
Representative application of desulfurized gypsum in synthetic materials.

Application	Utilization method	Advantagement	References
Alpha-hemihydrate gypsum	L-glutamate embedding	α-HH aspect ratio (~1:200)	Teng et al. (2018)
	the calcination-hydration treatment of FGD gypsum, increasing the glycerol content from 55% to 85%	α-HH content increased to 94.65%	Guan et al. (2019)
	salt concentration 20–30%; operation temperature 95–100 °C, solids mass content in the slurry 10–30%	α-HH with a fine columnar shape in 30 min	Wu et al. (2011)
	the concentration of Ca^{2+}, Mg^{2+} and glucose were 2.9, 0.0315 and 0.0370 mol/L, the volume ratio of glycerol 6%, the reaction time 4 h, reaction temperature 92 °C	α-HH aspect ratio (~35:1), the length (100 μm)	Yang et al. (2019)
	25 wt% $CaCl_2$, 2.0 wt% $MgCl_2$, and 1.0 wt% KCl; temperature 94 ± 2 °C	α-HH reaction time (3.5–6.0 h), the purity (95%); 3-day compressive strength (15.7–25.3 MPa)	Guan et al. (2011)
Carbonation	~10 vol% CO_2 gas; 120 wt% ammonia; solid-to-solution ratio (15 wt%)	carbonation conversion efficiency (96%)	Lee et al. (2015)
	solid-liquid ratio (10 wt%); $NH_3{\cdot}H_2O$ to $CaSO_4{\cdot}2H_2O$: 2.4 (mole ratio); CO_2 flow rate (150 ml/min)	carbonation products are vaterite (~60%) and calcite (~40%)	Wang et al. (2019)
Sulfur recovery	FeS_2:$CaSO_4$ = 1:3.5, the ventilation flow rate 1 L/min, temperature 1000 °C	the concentration of SO_2 was 2546.5 ppm	Song et al. (2019)
	reaction temperature (60 °C); residence time (4 h); solution system ($(NH_4)_2CO_3$)	ammonium sulfate yields (up to 83%) and purity (99%)	Chou et al. (2005)
Composite material	water–solid ratio (0.9 wt%); super plasticizer (2 wt%); foaming agent (0.2 wt%); waste textile fiber (3 wt%)	7-day compressive strengths (1.6 MPa); density (617 kg/m^3)	Liu et al. (2017)
	fly ash (90%), FGD gypsum (10%); reaction temperature and time (800 °C and 1 h)	compressive strengths 37.0 MPa	Guo et al. (2013)
	1% Maleic anhydride grafted polyethylene (MAgPE) as a compatibilizer, 70% recycled polyethylene (rPE) as a binder	gypsum load (50%)	Bilici et al. (2019)
Adsorption material	FGD gypsum (3 g/L); pH (5–11)	fluoride removal rate (93.31%)	Kang et al. (2019)
	CO_2 gas (15%); flow rate (10 L/min); initial reaction temperature (50 °C)	maximum adsorption capacity of Cd(II) (7.99 mg/g)	(Song, K. et al., 2011)
	Cr(VI) and V(V): pH (2.5), FGD gypsum (29.5 g/L), reaction time (10 min); Cr and V: pH (7.5), reaction time (15 min)	residual concentrations: Cr(VI) (0.163 mg/L), total Cr (0.395 mg/L) and total V (0.155 mg/L)	Fang et al. (2018)
	pH (2), FGD gypsum (1 g/L), the ratio of Fe (III)/Pb(II) (1:1)	the removal rate (90%)	(Li, R. et al., 2019)
	calcination treatment (600 °C)	improves the phosphate binding capacity (600 °C FGD gypsum 22.82 mg/g)	Cheng et al. (2018)

Fig. 4. Schematic drawing of the formation mechanism of α-HH (Guan et al., 2017a; Jia et al., 2020).

There are several ways to promote this transition (Miao et al., 2015). L-glutamic acid can promote the conversion when it is embedded in a layered CSD structure, converting FGD gypsum into α-HH whiskers (Teng et al., 2018). By increasing the glycerol content in the glycerol-water mixture from 55% to 85%, the conversion from the center point of $CaSO_4$ to the center point $1/2H_2O$(HH) can be promoted (Guan et al., 2019; Guan et al., 2017b). At the same time, many scholars have studied the synthesis of hemihydrate gypsum in a salt solution system. Due to different solubility, FGD gypsum can be directly converted into α-HH in a hot salt solution under atmospheric pressure (Wu et al., 2011). Under mild salt solution conditions, FGD gypsum is successfully converted into high-purity α-HH by solution recrystallization (Yang et al., 2019; Yang et al., 2009). At present, the preparation of α-HH under the salt solution system is the most important method, and there have been successful pilot scale trials (Guan et al., 2011). The transformation temperature and stirring speed have a main influence on the transformation process (Tang et al., 2015). In addition, the impurities in gypsum will also have a certain impact. $CaCO_3$ in FGD gypsum impurities will hinder the production of a-HH, because $CaSO_3$ blocks the a-HH nucleation site. Washing off $CaSO_3$ can greatly increase the conversion rate (Fu et al., 2017). With the study of the transformation process, many scholars have also conducted in-depth studies on the size and crystal form of the α-HH. In the process of controlling the hemihydrate gypsum phase and crystalline form, a crystallization regulator can be added to adjust and control its crystalline form and the quantity of fine whiskers (Ma et al., 2018; Zhang, X.F. et al., 2016). The use of magnesium chloride reduces the average length and aspect ratio of hemihydrate gypsum, while a small amount of citric acid or sodium

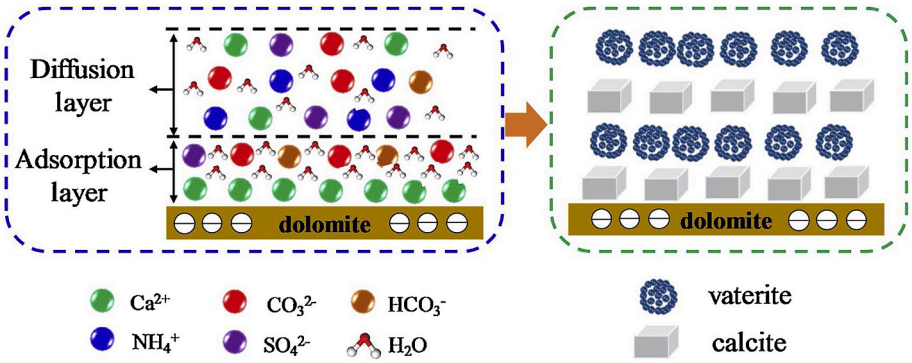

Fig. 5. FGD gypsum carbonation reaction process (Wang et al., 2019).

dodecyl benzene sulfonate can improve the morphology (Liu et al., 2016). A smaller gypsum particle size reduces the overall activation energy barrier for conversion. Over-adjusting the particle size of FGD gypsum can effectively promote its conversion to α-HH (Fu et al., 2018). Different ions have different effects on the conversion process. The simultaneous addition of Mg^{2+} and Fe^{3+} will increase the induction time and reduce the growth efficiency by 50% (Gao et al., 2008). NaCl can effectively promote the dissolution of calcium sulfate dihydrate, thereby speeding up the conversion process-(Guan et al., 2017a). $CuCl_2$ will make the produced α-HH have a single crystal structure with a very smooth surface (Wang et al., 2015). Both the dissolution characteristics of FGD gypsum and the crystal form of the whiskers are affected by anions. The strength of Cu-O binding energy is highest under the action of NO_3^-, next to the action of SO_4^{2-}, and weakest under the action of Cl^- (Wang, X. et al., 2020). The composition of the solution also has potential effects, and the optimal system is the H_2SO_4-NaCl-H_2O system (Wang et al., 2014).

3.3.2. Carbonation

Reducing carbon dioxide is a key measure to reduce the greenhouse effect. The long-term stability of the reaction product due to the solidification of minerals has attracted more and more attention. Using fly ash and FGD gypsum as reaction raw materials, solid-waste sequestering of carbon dioxide under normal temperature and pressure conditions has also become a hot research topic. It is completely feasible to use CO_2 gas to carbonize FGD gypsum. Carbon dioxide gas is introduced into the mixed system containing FGD gypsum and ammonia solution, and FGD gypsum can be carbonized into $CaCO_3$. The process is shown in Fig. 5 and the reaction is as follows:

$$CaSO_4{\cdot}2H_2O(s) + CO_2(g) + 2NH_4OH\ (aq) \rightarrow (NH_4)_2SO_4(aq) + CaCO_3(s) + 2H_2O$$

Both carbonization temperature and impurities have a significant impact on the carbonization process. The carbonation reaction at 40 °C is almost twice that at room temperature (Lee et al., 2015). Impurities can affect the polymorph of $CaCO_3$ (Wang et al., 2019). Song used calcium carbonate prepared from FGD gypsum to absorb Cd(II), with a removal rate of about 90%, and realized the treatment of wastewater after carbonation (Song, Kyungsun et al., 2011). The carbonation process is beneficial to reduce the mercury in FGD gypsum. Several researchers have studied the change of mercury form during the carbonation process and confirmed it by the continuous chemical extraction (SCE) method. The mercury content in all the original FGD gypsum samples exceeded level 2 (1 μg/g) of the Chinese national standard, and the Hg content in the carbonated samples after the wet FGD process decreased because carbonate and ammonia complexes can change the form of mercury and reduce the Hg content (Tan et al., 2018).

3.3.3. Sulfur recovery

In order to effectively recover the valuable part of FGD gypsum, many scholars have studied the recovery of sulfur resources through high-temperature reduction of FGD gypsum. The reduction reaction process of FGD gypsum is very complicated, and depends on the reduction temperature and reducing agent. Properly increasing the ratio of C/$CaSO_4$ as well as the temperature produces conditions suitable for forming the main product of CaO, thereby promoting the recovery of sulfur resources (Zheng et al., 2013). By adding pyrite, the FGD gypsum is reduced and decomposed to recover its sulfur resources. The mixture of FGD gypsum and pyrite is added to a boiling furnace and the remaining heat is used to prepare sulfur dioxide (Song et al., 2019). At the same time, FGD gypsum is reacted with $(NH_4)_2CO_3$ in an aqueous solution to produce $(NH_4)_2SO_4$. Under relatively mild conditions, high yield (up to 83%) of $(NH_4)_2SO_4$ can be obtained with a purity of up to 99%. The production of ammonium sulfate fertilizer from FGD gypsum demonstrated that sulfur resources can be recovered through recycling (Chou et al., 2005).

3.3.4. Composite material

The preparation of composite materials by synergistic utilization of different substances and FGD gypsum is another focus of current research. Many scholars use FGD gypsum together with other materials. For example, Liu used FGD gypsum mixed textile fibers to make foam concrete. The 7-day compressive strength was 1.6 MPa, and the density was 617 kg/m^3. This composite material has better utilization value in building materials (Liu et al., 2017). Guo studied the feasibility of using FGD gypsum and fly ash to prepare geopolymers. The compressive strength is 37.0 MPa, and FGD gypsum participates in the reaction during the activation and polymerization process (Guo et al., 2013). Bilici uses FGD gypsum and recycled polyethylene to prepare a composite matrix, and the resulting composite material has a good melt flow rate (Bilici et al., 2019). Zhong studied the thermal decomposition of potassium feldspar and FGD gypsum industrial waste to produce soluble potassium salt, and the recovery of K was higher than 90% (Zhong et al., 2017).

3.3.5. Adsorption material

Because FGD gypsum has good adsorption and reducibility, it is often used as an adsorption material, especially for elements such as F, S, Cr, V, P, Pb, Cd and Zn. The removal rate of fluoride by FGD gypsum is 93.31%, demonstrating that fluoride can be effectively removed (Kang et al., 2019). Calcite waste produced by the carbonation reaction of FGD gypsum, which is a low-cost adsorbent for wastewater desulfurization (Song, K. et al., 2011). FGD gypsum can also be used as a reducing agent to reduce chromium and vanadium, thereby removing them in the form of precipitation (Fang et al., 2018). The calcination of FGD gypsum is used as a phosphate adsorption material to treat phosphate wastewater.

Roasting improves the adsorption performance of FGD gypsum for phosphate. The calcined desulfurized gypsum is mainly precipitated by chemical adsorption, and the phosphate is finally fixed by hydroxyapatite. Roasted desulfurized gypsum has a good dephosphorization capacity (Cheng et al., 2018). Chang uses FGD gypsum as a carrier to synthesize a solid diamine adsorbent with 2-[2-(dimethylamine) ethoxy] ethanol (DMAEE) and pentaacetonitrile (PEHA), and its adsorption effect is better than that of a single adsorbent (Chang et al., 2020). As an adsorbent, FGD gypsum has a good adsorption effect on lead and zinc heavy metal ions. Li used an Fe(III)/FGD gypsum system to remove Pb(II); 97.35% of Pb(II) chelated by EDTA is removed (Li, R. et al., 2019). Yan uses FGD gypsum to remove Pb(II) and Cd(II) in industrial wastewater and obtains a good removal effect, which has good industrial application significance (Yan et al., 2014; Yan et al., 2015). At the same time, many scholars have used FGD gypsum to prepare adsorption materials and apply them in actual production. They use FGD gypsum to treat coal ash (CA) landfill leachate. Sulfate-reducing bacteria (SRB) use the soluble sulfate in FGD gypsum; it acts as an electron acceptor to generate hydrogen sulfide (H_2S). Sulfide-rich wastewater produced by the sulfate reduction method is used to precipitate HMs in CBA leachate as metal sulfides. Through sulfide precipitation, the removal rate of HM is between 40 and 100% (Jayaranjan and Annachhatre, 2013). FGD gypsum removes odorous substances geosmin and 2-methylisoborneol (MIB) in fish-pond water. FGD gypsum can also effectively reduce the concentration of chlorophyll *a* and orthophosphate through calcium phosphate precipitation (Whangchai et al., 2016). FGD waste removes silicate in scheelite flotation wastewater. The silicate removal rate reaches 90% under the optimal conditions, which proves the feasibility of using FGD gypsum to remove silicate (Kang et al., 2018).

3.4. Application of FGD gypsum to soil

Because FGD gypsum is rich in sulfur/calcium resources, it is widely used in soil remediation. FGD gypsum can be used as an improver of saline-alkaline soil (Sakai et al., 2004); this is a safe and effective method for the recovery of saline-sodic soils (Zhao, Y.G. et al., 2018a). Corn production has been increased with this method. After the treatment, the soil chemical parameters are restored, and the agricultural output of each field increases. Many studies have confirmed the improvement effect of FGD gypsum on saline soil (Li and Wang, 2018; Sakai et al., 2011). The release of toxic elements such as Hg, As, Pb, Co, Cd and Cr in FGD gypsum-mixed soil under different environmental conditions can be ignored (Koralegedara et al., 2019a); the concentrations of all these metals in the soil and even in the plants growing on the soil, are below the standard values for human intake specified by the FAO/WHO. Soil organic carbon analysis shows that saline-alkali soil amendment can fix more carbon, thereby helping to slow down global warming (Han et al., 2016; Wang et al., 2017). The mudflat soil of the Yangtze River Estuary was repaired with FGD gypsum. The improvement effect is achieved after 6 months, and there is still improvement after 18 months. The use of high-strength gypsum to repair tidal flat soil has broad application prospects (Mao et al., 2016). Tieshanping carried out a one-year trial of restoration of typical acidified forest soil with FGD gypsum, and the concentrations of As, Cu, Cr, Ni and Zn in soil moisture did not increase significantly, even though Cr, Ni and Zn in the surface soil are slightly enriched (Luo et al., 2012). Many scholars have evaluated the effects of FGD gypsum on soil salinity, crop yield and harmful element content. FGD gypsum changed the main water-soluble ion concentration, the concentration of Ca^{2+} and SO_4^{2-} increased, while the concentration of HCO^{3-} and CO_3^{2-} decreased. After reclamation, the output of crops gradually increased, and the output of sunflower and corn became the main local crops. In addition, the content of harmful elements in soil and crops is far below the prescribed standards, and even below the detection limit (Li et al., 2012; Li, X. et al., 2015; Nan et al., 2016a; Yang et al., 2018; Zhao, Y.G. et al., 2018b; Zhao et al., 2019b). Because slowly dissolving lime requires excessive time to improve the aggregation of the soil, water and nutrients can penetrate the soil more quickly. Due to the high solubility and high calcium and sulfur content of FGD gypsum, it can effectively provide sulfur resources in the soil by increasing infiltration and soil water content, reducing runoff, and mitigating the exchangeable aluminum problem (Rhoton and McChesney, 2011b). FGD gypsum can also be used to reduce soil moisture and extract phosphorus, thereby reducing the potential for phosphorus to be exported to surface water, remediating high-phosphorus soil (He et al., 2018; Stout et al., 2003; Wang et al., 2013). When FGD gypsum improves the soil, the soil moisture concentration increases the reclamation efficiency in the first 30 days, and gradually decreases with time. Therefore, FGD gypsum can be used for sodium soil recovery in low-water areas. Appropriate increases in its application rate and/or reaction time with soil can improve its recovery effect (Zhao et al., 2020). FGD gypsum can effectively reduce the erodibility of these sodium soils, increase soil infiltration, and reduce reverse osmosis reaction and soil loss. The formation of large sediment particles has shown that as the proportion of finer sediments in RO decreases, the quality of surface water will be improved (Liao et al., 2019; Presley et al., 2018; Rhoton and McChesney, 2011a). FGD gypsum can effectively repair sodium soil by improving the two-dimensional/three-dimensional pore characteristics of the soil, especially the vertical macropore characteristics (Chen et al., 2015; Ishak et al., 2002; Liao et al., 2020; Yu et al., 2014).

Despite all these benefits, the application of FGD gypsum to soil has caused scholars to become increasingly concerned about the potential harmful elements of FGD, as it will bring additional heavy metal pollution into the soil environment, especially elements such as mercury and arsenic. Excessive application of FGD gypsum will increase the concentration of mercury and increase the mercury content in soil, plants, and the atmosphere. However, some plants, such as tall fescue, can prevent mercury from being emitted into the atmosphere and permeating into the soil. It was found that the concentration of mercury in plant stems first increased and then stabilized, when the amount of FGD gypsum applied to the soil was increased. The leaves of the plants probably absorbed some mercury from the atmosphere. Regarding the heavy metals in FGD, however, a large number of studies have shown that the heavy metal content in the remediated soil meets the Chinese Soil Environmental Quality Standard (GB15618-1995) (Wang, K.L. et al., 2013; Yang et al., 2016; Zhao, Y.G. et al., 2018a).

4. Conclusions and perspective

This article has discussed the development process of China's FGD gypsum and its beneficial uses. The following conclusions were obtained.

First, based on the basic properties of China's FGD gypsum, although the content of harmful elements is relatively small, it still contains metals such as mercury, and other harmful elements. At present, many studies have confirmed that the concentrations of heavy metals resulting from the application of FGD gypsum is generally negligible, although some applications (such as promoting plant growth, producing wallboard materials, etc.) still need attention.

Second, the main research on the application of FGD gypsum is concentrated in the four fields of building materials, agriculture, soil, and material synthesis. In terms of building materials, FGD gypsum is mainly used in replacing cement clinker, while in agricultural and soil application, FGD gypsum is mainly used for its calcium and sulfur elements, to improve soil fertility, promote crop yields, and reduce soil salinity. In these applications, the large-scale application of FGD gypsum

has been promoted, but its added value is low. In terms of material synthesis, the research still focuses on the preparation of synthetic dihydrate gypsum. In this regard, although higher value-added products can be prepared, it is not suitable for large-scale application due to its harsh preparation conditions.

Exploring large-scale application and generating higher value-added utilization is an urgent problem to be explored for the reuse of FGD gypsum. Based on a summary of the beneficial applications of FGD gypsum, our research team proposed a new way of using it. Calcium sulfide products can be prepared by reducing and sintering FGD gypsum. The sulfur in calcium sulfide can effectively remove heavy metals. The hydrogen sulfide gas produced by the solid-liquid reaction removes heavy metals in wastewater. The calcium generated by the solid-liquid reaction is returned to the desulfurization process for reuse, which not only solves the problem of the mass production of FGD gypsum from the source, but also enables the development of high-value applications.

Credit author statement

Sen Liu: Investigation, Data processing, Methodology, Writing – original draft. Wei Liu: Supervision, Funding acquisition, Writing – review & editing. Jiao Fen: Funding acquisition, Writing – review & editing. Wenqing Qin: Conceptualization, Writing – review & editing. Congren Yang: Investigation, Methodology, Data processing, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Key R&D Program of China (2020YFC1909203), National Natural Science Foundation of China (51874356), Key Laboratory of Hunan Province for Clean and Efficient Utilization of Strategic Calcium-containing Mineral Resources (No. 2018TP1002).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2021.117799.

References

Al-Abed, S.R., Jegadeesan, G., Scheckel, K.G., Tolaymat, T., 2008. Speciation, characterization, and mobility of As, Se, and Hg in flue gas desulphurization residues. Environ. Sci. Technol. 42 (5), 1693–1698.
Alvarez-Ayuso, E., Querol, X., 2007. Stabilization of FGD gypsum for its disposal in landfills using amorphous aluminium oxide as a fluoride retention additive. Chemosphere 69 (2), 295–302.
Alvarez-Ayuso, E., Querol, X., Ballesteros, J.C., Gimenez, A., 2008. Risk minimisation of FGD gypsum leachates by incorporation of aluminium sulphate. Sci. Total Environ. 406 (1–2), 69–75.
Bilici, I., Deniz, C.U., Oz, B., 2019. Thermal and mechanical characterization of composite produced from recycled PE and flue gas desulfurization gypsum. J. Compos. Mater. 53 (23), 3325–3333.
Caillahua, M.C., Moura, F.J., 2018. Technical feasibility for use of FGD gypsum as an additive setting time retarder for Portland cement. J. Mater. Res. Technol-JMRT 7 (2), 190–197.
Chang, J., Hou, C.M., Wan, D.H., Zhang, X.L., Xu, B., Tian, H.J., Wang, X., Guo, Q.J., 2020. Enhanced CO2 adsorption capacity of bi-amine co-tethered flue gas desulfurization gypsum with water of hydration. J. CO2 Util. 35, 115–125.
Chen, L.M., Dick, W.A., Nelson, S., 2005. Flue gas desulfurization products as sulfur sources for alfalfa and soybean. Agron. J. 97 (1), 265–271.
Chen, Q., Wang, S.J., Li, Y., Zhang, N., Zhao, B., Zhuo, Y.Q., Chen, C.H., 2015. Influence of flue gas desulfurization gypsum amendments on heavy metal distribution in reclaimed sodic soils. Environ. Eng. Sci. 32 (6), 470–478.
Cheng, P., Chen, D., Liu, H.B., Zou, X.H., Zhang, Y.Q., Xie, J.J., Qing, C.S., Chen, T.H., 2018. Enhanced adsorption capacity for phosphate in wastewater from thermally activated flue gas desulfurization gypsum. J. Chem. Technol. Biotechnol. 93 (6), 1733–1741.
Chou, M.I.M., Bruinius, J.A., Benig, V., Chou, S.F.J., Carty, R.H., 2005. Producing ammonium sulfate from flue gas desulfurization by-products. Energy Sources 27 (11), 1061–1071.
Clark, R.B., Baligar, V.C., 2003. Growth of forage legumes and grasses in acidic soil amended with flue gas desulfurization products. Commun. Soil Sci. Plant Anal. 34 (1–2), 157–180.
Codling, E.E., Lewis, J., Watts, D.B., 2015. Broiler litter ash and flue gas desulfurization gypsum effects on peanut yield and uptake of nutrients. Commun. Soil Sci. Plant Anal. 46 (20), 2553–2575.
Cordoba, P., Castro, I., Maroto-Valer, M., Querol, X., 2015. The potential leaching and mobilization of trace elements from FGD-gypsum of a coal-fired power plant under water re-circulation conditions. J. Environ. Sci. 32, 72–80.
Cordon, H.C.F., Cagnoni, F.C., Ferreira, F.F., 2019. Comparison of physical and mechanical properties of civil construction plaster and recycled waste gypsum from Sao Paulo, Brazil. J. Build. Eng. 22, 504–512.
DeSutter, T.M., Cihacek, L.J., Rahman, S., 2014. Application of flue gas desulfurization gypsum and its impact on wheat grain and soil chemistry. J. Environ. Qual. 43 (1), 303–311.
Desutter, T.M., Lukach, J., Cihacek, L.J., 2011. Sulfur fertilization of canola (Brassica napus) with flue gas desulfurization gypsum: an assessment study. Commun. Soil Sci. Plant Anal. 42 (20), 2537–2547.
Diao, X., Yuan, C.G., Wu, J.J., Gui, B., Zhang, K.G., Zhang, C., 2018. Mercury release and fraction transformation during desulfurization gypsum aging process (UV irradiation). Fuel 217, 522–528.
Endale, D.M., Schomberg, H.H., Fisher, D.S., Franklin, D.H., Jenkins, M.B., 2014. Flue gas desulfurization gypsum: implication for runoff and nutrient losses associated with broiler litter use on pastures on ultisols. J. Environ. Qual. 43 (1), 281–289.
Fang, D., Liao, X., Zhang, X.F., Teng, A.J., Xue, X.X., 2018. A novel resource utilization of the calcium-based semi-dry flue gas desulfurization ash: as a reductant to remove chromium and vanadium from vanadium industrial wastewater. J. Hazard. Mater. 342, 436–445.
Febrisiantosa, A., Ravindran, B., Choi, H.L., 2018. The effect of Co-additives (biochar and FGD gypsum) on ammonia volatilization during the composting of livestock waste. Sustainability 10 (3), 18.
Fu, B., Liu, G.J., Mian, M.M., Sun, M., Wu, D., 2019. Characteristics and speciation of heavy metals in fly ash and FGD gypsum from Chinese coal-fired power plants. Fuel 251, 593–602.
Fu, H., Jia, C., Chen, Q., Cao, X., Zhang, X., 2018. Effect of particle size on the transformation kinetics of flue gas desulfurization gypsum to alpha-calcium sulfate hemihydrate under hydrothermal conditions. Particuology 40, 98–104.
Fu, H.L., Huang, J.S., Yin, L.W., Yu, J., Lou, W.B., Jiang, G.M., 2017. Retarding effect of impurities on the transformation kinetics of FGD gypsum to alpha-calcium sulfate hemihydrate under atmospheric and hydrothermal conditions. Fuel 203, 445–451.
Gao, X., Huo, W., Zhong, Y., Luo, Z.Y., Cen, K.F., Ni, M.J., Chen, L.M., 2008. Effects of magnesium and ferric ions on crystallization of calcium sulfate dihydrate under the simulated conditions of wet flue-gas desulfurization. Chem. Res. Chin. Univ. 24 (6), 688–693.
Guan, B., Lou, W., Ye, Q., Fu, H., Wu, Z., 2009. Calorimetric study of calcium aluminate cement blended with flue gas desulfurization gypsum. J. Therm. Anal. Calorim. 98 (3), 737–742.
Guan, B.H., Yang, L., Fu, H.L., Kong, B., Li, T.Y., Yang, L.C., 2011. alpha-calcium sulfate hemihydrate preparation from FGD gypsum in recycling mixed salt solutions. Chem. Eng. J. 174 (1), 296–303.
Guan, Q.J., Sun, W., Guan, C.P., Yu, W.J., Zhu, X.N., Khoso, S.A., Wang, P., Peng, W.Q., 2019. Promotion of conversion activity of flue gas desulfurization gypsum into alpha-hemihydrate gypsum by calcination-hydration treatment. J. Cent. South Univ. 26 (12), 3213–3224.
Guan, Q.J., Sun, W., Hu, Y.H., Yin, Z.G., Guan, C.P., 2017a. Synthesis of alpha-CaSO4 center dot 0.5H(2)O from flue gas desulfurization gypsum regulated by C4H4O4Na2 center dot 6H(2)O and NaCl in glycerol-water solution. RSC Adv. 7 (44), 27807–27815.
Guan, Q.J., Tang, H.H., Sun, W., Hu, Y.H., Yin, Z.G., 2017b. Insight into influence of glycerol on preparing alpha-CaSO4 center dot 1/2H(2)O from flue gas desulfurization gypsum in glycerol water solutions with succinic acid and NaCI. Ind. Eng. Chem. Res. 56 (35), 9831–9838.
Guo, X.B., Lu, Y.Y., Li, Q.L., 2016. Effect of adding flue gas desulphurization gypsum on the transformation and fate of nitrogen during composting. Compost Sci. Util. 24 (4), 230–237.
Guo, X.L., Shi, H.S., Dick, W.A., 2013. Utilization of thermally treated flue gas desulfurization (FGD) gypsum and class-C Fly Ash (CFA) to prepare CFA-based geopolymer. J. Wuhan Univ. Technol.-Mat. Sci. Edit. 28 (1), 132–138.
Han, M., Yi, S.T., Yoon, W., 2019. Effect of WRP and FGD gypsum on engineering properties and microstructures of HVBSM. Green Mater. 7 (2), 97–108.
Han, Y.S., Tokunaga, T.K., Salve, R., Chon, C.M., 2016. Environmental feasibility of soil amendment with flue gas desulfurization gypsum (FGDG) for terrestrial carbon sequestration. Environ. Earth Sci. 75 (15), 9.
Hao, Y., Li, Q., Pan, Y., Liu, Z.X., Wu, S.M., Xu, Y.B., Qian, G.R., 2017. Heavy metals distribution characteristics of FGD gypsum samples from Shanxi province 12 coal-fired power plants and its potential environmental impacts. Fuel 209, 238–245.
Hao, Y., Wu, S., Pan, Y., Li, Q., Zhou, J., Xu, Y., Qian, G., 2016. Characterization and leaching toxicities of mercury in flue gas desulfurization gypsum from coal-fired power plants in China. Fuel 177, 157–163.

He, K., Li, X.P., 2019. Inhibiting effects of flue gas desulfurization gypsum on soil phosphorus loss in Chongming Dongtan, southeastern China. Environ. Sci. Pollut. Res. 26 (17), 17195–17203.
He, K., Li, X.P., Dong, L.L., 2018. The effects of flue gas desulfurization gypsum (FGD gypsum) on P fractions in a coastal plain soil. J. Soils Sediments 18 (3), 804–815.
Hua, M.J., Wang, B.T., Chen, L.M., Wang, Y.H., Quynh, V.M., He, B., Li, X.F., 2010. Verification of lime and water glass stabilized FGD gypsum as road sub-base. Fuel 89 (8), 1812–1817.
Ishak, C.F., Seaman, J.C., Miller, W.P., Sumner, M., 2002. Contaminant mobility in soils amended with fly ash and flue-gas gypsum: intact soil cores and repacked columns. Water Air Soil Pollut. 134 (1–4), 287–305.
Jayaranjan, M.L.D., Annachhatre, A.P., 2013. Precipitation of heavy metals from coal ash leachate using biogenic hydrogen sulfide generated from FGD gypsum. Water Sci. Technol. 67 (2), 311–318.
Jenkins, M.B., Schomberg, H.H., Endale, D.M., Franklin, D.H., Fisher, D.S., 2014. Hydrologic transport of fecal bacteria attenuated by flue gas desulfurization gypsum. J. Environ. Qual. 43 (1), 297–302.
Jia, C.Y., Wu, L.C., Chen, Q.S., Lin, J.M., Yang, L., Song, Z.R., Guan, B.H., 2020. Distribution behavior of arsenate into alpha-calcium sulfate hemihydrate transformed from gypsum in solution. Chemosphere 255, 9.
Jiang, B.F., Xie, Y.L., Xia, D.H., Liu, X.J., 2019. A potential source for PM2.5: analysis of fine particle generation mechanism in Wet Flue Gas Desulfurization System by modeling drying and breakage of slurry droplet. Environ. Pollut. 246, 249–256.
Jiang, L.H., Li, C.Z., Wang, C., Xu, N., Chu, H.Q., 2018. Utilization of flue gas desulfurization gypsum as an activation agent for high-volume slag concrete. J. Clean. Prod. 205, 589–598.
Jimenez-Rivero, A., Garcia-Navarro, J., 2016. Indicators to measure the management performance of end-of-life gypsum: from deconstruction to production of recycled gypsum. Waste Biomass Valorization 7 (4), 913–927.
Jimenez-Rivero, A., Garcia-Navarro, J., 2017a. Best practices for the management of end-of-life gypsum in a circular economy. J. Clean. Prod. 167, 1335–1344.
Jimenez-Rivero, A., Garcia-Navarro, J., 2017b. Exploring factors influencing post-consumer gypsum recycling and landfilling in the European Union. Resour. Conserv. Recycl. 116, 116–123.
Kang, J.H., Gou, X.Q., Hu, Y.H., Sun, W., Liu, R.Q., Gao, Z.Y., Guan, Q.J., 2019. Efficient utilisation of flue gas desulfurization gypsum as a potential material for fluoride removal. Sci. Total Environ. 649, 344–352.
Kang, J.H., Hu, Y.H., Sun, W., Liu, R.Q., Gao, Z.Y., Guan, Q.J., Tang, H.H., Yin, Z.G., 2018. Utilisation of FGD gypsum for silicate removal from scheelite flotation wastewater. Chem. Eng. J. 341, 272–279.
Katolicky, J., Jicha, M., 2013. Influence of the lime slurry droplet spectrum on the efficiency of semi-dry flue gas desulfurization. Chem. Eng. Technol. 36 (1), 156–166.
King, K.W., Williams, M.R., Dick, W.A., LaBarge, G.A., 2016. Decreasing phosphorus loss in tile-drained landscapes using flue gas desulfurization gypsum. J. Environ. Qual. 45 (5), 1722–1730.
Klaka, T., Kaiser, S., Barbe, S., 2018. Numerical simulation of industrial dry flue-gas desulfurization processes. Chem. Ing. Tech. 90 (6), 836–840.
Koralegedara, N.H., Al-Abed, S.R., Arambewela, M.K.J., Dionysiou, D.D., 2019a. Impact of leaching conditions on constituent release from Flue Gas Desulfurization Gypsum (FGDG) and FGDG-soil mixture (vol 324, pg 83, 2017). J. Hazard. Mater. 379, 4.
o.E.M. Koralegedara, N.H., Pinto, P.X., Dionysiou, D.D., Al-Abed, S.R.J.J., 2019b. Recent Advances in Flue Gas Desulfurization Gypsum Processes and Applications -A Review, p. 251.
Koukouzas, N., Vasilatos, C., 2008. Mineralogical and chemical properties of FGD gypsum from Florina, Greece. J. Chem. Technol. Biotechnol. 83 (1), 20–26.
Lancia, A., Musmarra, D., 1999. Calcium bisulfite oxidation rate in the wet limestone-gypsum flue gas desulfurization process. Environ. Sci. Technol. 33 (11), 1931–1935.
Lee, J.-Y., Cho, K., Cheng, L., Keener, T.C., Jegadeesan, G., Al-Abed, S.R., 2009. Investigation of a mercury speciation technique for flue gas desulfurization materials. J. Air Waste Manag. Assoc. 59 (8), 972–979.
Lee, M.G., Ryu, K.W., Chae, S.C., Jang, Y.N., 2015. Effects of temperature on the carbonation of flue gas desulphurization gypsum using a CO2/N-2 gas mixture. Environ. Technol. 36 (1), 106–114.
Lei, D.Y., Guo, L.P., Sun, W., Liu, J.P., Miao, C.W., 2017. Study on properties of untreated FGD gypsum-based high-strength building materials. Construct. Build. Mater. 153, 765–773.
Li, H.X., Zhang, H., Li, L., Ren, Q., Yang, X.J., Jiang, Z.W., Zhang, Z.L., 2019. Utilization of low-quality desulfurized ash from semi-dry flue gas desulfurization by mixing with hemihydrate gypsum. Fuel 255, 8.
Li, J., Zhuang, X., Leiva, C., Cornejo, A., Font, O., Querol, X., Moeno, N., Arenas, C., Fernandez-Pereira, C., 2015. Potential utilization of FGD gypsum and fly ash from a Chinese power plant for manufacturing fire-resistant panels. Construct. Build. Mater. 95, 910–921.
Li, J., Zhuang, X.G., Querol, X., Font, O., Moreno, N., 2018. A review on the applications of coal combustion products in China. Int. Geol. Rev. 60 (5–6), 671–716.
Li, J.Y., Wang, J.M., 2018. Integrated life cycle assessment of improving saline-sodic soil with flue gas desulfurization gypsum. J. Clean. Prod. 202, 332–341.
Li, M., Jiang, L.L., Sun, Z.J., Wang, J.Z., Rui, Y.C., Zhong, L., Wang, Y.F., Kardol, P., 2012. Effects of flue gas desulfurization gypsum by-products on microbial biomass and community structure in alkaline-saline soils. J. Soils Sediments 12 (7), 1040–1053.
Li, R., Li, Q., Sun, X.Y., Li, J.S., Shen, J.Y., Han, W.Q., Wang, L.J., 2019. Efficient and rapid removal of EDTA-chelated Pb(II) by the Fe(III)/flue gas desulfurization gypsum (FGDG) system. J. Colloid Interface Sci. 542, 379–386.
Li, X., Mao, Y., Liu, X., 2015. Flue gas desulfurization gypsum application for enhancing the desalination of reclaimed tidal lands. Ecol. Eng. 82, 566–570.
Liao, R.K., Yu, H.L., Lin, H., Yang, P.L., 2019. A quantitative study on three-dimensional pore parameters and physical properties of sodic soils restored by FGD gypsum and leaching water. J. Environ. Manag. 248, 10.
Liao, R.K., Yu, H.L., Yang, P.L., Lin, H., 2020. Quantitative evaluation of pore characteristics of sodic soils reclaimed by flue gas desulphurization gypsum using X-ray computed tomography. Land Degrad. Dev. 31 (5), 545–556.
Liu, C.J., Zhao, Q., Wang, Y.G., Shi, P.Y., Jiang, M.F., 2016. Hydrothermal synthesis of calcium sulfate whisker from flue gas desulfurization gypsum. Chin. J. Chem. Eng. 24 (11), 1552–1560.
Liu, X., Wang, S., Zhang, L., Wu, Y., Duan, L., Hao, J., 2013. Speciation of mercury in FGD gypsum and mercury emission during the wallboard production in China. Fuel 111, 621–627.
Liu, Y., Li, Q.Y., Yan, A.M., 2001. Comment on "Calcium bisulfite oxidation rate in the wet limestone-gypsum flue gas desulfurization process". Environ. Sci. Technol. 35 (15), 3270–3271.
Liu, Y.Y., Zhang, Y.H., Guo, Y.X., Chu, P.K., Tu, S.C., 2017. Porous materials composed of flue gas desulfurization gypsum and textile fiber wastes. Waste Biomass Valorization 8 (1), 203–207.
Luo, Y., Kang, R.-h., Yu, D.-x., Tan, B.-q., Duan, L., 2012. Effect of flue gas desulfurization gypsum application on remediation of acidified forest soil. Huanjing Kexue 33 (6), 2006–2012.
Ma, X.L., Tan, H.B., He, X.C., 2018. Preparation and surface modification of anhydrous calcium sulfate whiskers from FGD gypsum iii autoclave-free hydrothermal system. Energy Sources, Part A Recovery, Util. Environ. Eff. 40 (17), 2055–2062.
Ma, Y.T., Nie, Q.K., Xiao, R., Hu, W., Han, B.Y., Polaczyk, P.A., Huang, B.S., 2020. Experimental investigation of utilizing waste flue gas desulfurized gypsum as backfill materials. Construct. Build. Mater. 245, 8.
Mao, Y.M., Li, X.P., Dick, W.A., Chen, L.M., 2016. Remediation of saline-sodic soil with flue gas desulfurization gypsum in a reclaimed tidal flat of southeast China. J. Environ. Sci. 45, 224–232.
MEE, 2000-2019. Report on the State of the Environment in China. Ministry of Ecology and Environment (MEE) of China, Beijing.
MEE, 2014-2019. Annual Report on the Prevention and Control of Solid Waste Pollution in Large and Medium Cities. Ministry of Ecology and Environment (MEE) of China.
Miao, M., Feng, X., Wang, G.L., Cao, S.M., Shi, W., Shi, L.Y., 2015. Direct transformation of FGD gypsum to calcium sulfate hemihydrate whiskers: preparation, simulations, and process analysis. Particuology 19, 53–59.
Michalovicz, L., Dick, W.A., Cervi, E.C., Tormena, C.A., Lopes Mueller, M.M., 2017. Flue gas desulfurization gypsum as a chemical amendment to reduce the concentrations of phosphorus and suspended solids in liquid manure. Manag. Environ. Qual. 28 (5), 624–631.
Michalski, J.A., 2017. Flue gas desulfurization methods in coal-fired power plant. Przem. Chem. 96 (4), 731–736.
Mishra, A., Cabrera, M.L., Rema, J.A., 2012. Phosphorus fractions in poultry litter as affected by flue-gas desulphurization gypsum and litter stacking. Soil Use Manag. 28 (1), 27–34.
Nan, J.K., Chen, X.M., Chen, C., Lashari, M., Deng, J.Q., Du, Z.J., 2016a. Impact of flue gas desulfurization gypsum and lignite humic acid application on soil organic matter and physical properties of a saline-sodic farmland soil in Eastern China. J. Soils Sediments 16 (9), 2175–2185.
Nan, J.K., Chen, X.M., Wang, X.Y., Lashari, M.S., Wang, Y.M., Guo, Z.C., Du, Z.J., 2016b. Effects of applying flue gas desulfurization gypsum and humic acid on soil physicochemical properties and rapeseed yield of a saline-sodic cropland in the eastern coastal area of China. J. Soils Sediments 16 (1), 38–50.
Pang, M., Sun, Z., Huang, H., 2020. Compressive strength and durability of FGD gypsum-based mortars blended with ground granulated blast furnace slag. Materials 13 (15).
Pantini, S., Giurato, M., Rigamonti, L., 2019. A LCA study to investigate resource-efficient strategies for managing post-consumer gypsum waste in Lombardy region (Italy). Resour. Conserv. Recycl. 147, 157–168.
Pedreno-Rojas, M.A., Fort, J., Cerny, R., Rubio-de-Hita, P., 2020. Life cycle assessment of natural and recycled gypsum production in the Spanish context. J. Clean. Prod. 253.
Phutthimethakul, L., Kumpueng, P., Supakata, N., 2020. Use of flue gas desulfurization gypsum, construction and demolition waste, and oil palm waste trunks to produce concrete bricks. Crystals 10 (8).
Prakaypun, W., Jinawath, S., 2003. Comparative effect of additives on the mechanical properties of plasters made from flue-gas desulfurized and natural gypsums. Mater. Struct. 36 (255), 51–58.
Presley, D., He, Y., Tomlinson, P., 2018. Soil health and yields on non-sodic soils amended with flue gas desulfurization gypsum. Crop Forage Turfgrass Manag 4 (1), 6.
Rhoton, F.E., McChesney, D.S., 2011a. Erodibility of a sodic soil amended with flue gas desulfurization gypsum. Soil Sci. 176 (4), 190–195.
Rhoton, F.E., McChesney, D.S., 2011b. Influence of FGD gypsum on the properties of a highly erodible soil under conservation tillage. Commun. Soil Sci. Plant Anal. 42 (16), 2012–2023.
Sakai, Y., Matsumoto, S., Sadakata, M., 2004. Alkali soil reclamation with flue gas desulfurization gypsum in China and assessment of metal content in corn grains. Soil Sediment Contam. 13 (1), 65–80.
Sakai, Y., Ren, S.R., Wang, C., Sadakata, M., 2011. Salt-affected soil amelioration with flue gas desulfurization by-products and waste gypsum board in tianjin, China. J. Chem. Eng. Jpn. 44 (10), 750–756.
Schomberg, H.H., Endale, D.M., Jenkins, M.B., Chaney, R.L., Franklin, D.H., 2018. Metals in soil and runoff from a piedmont hay field amended with broiler litter and flue gas desulfurization gypsum. J. Environ. Qual. 47 (2), 326–335.

Seo, S.K., Chu, Y.S., Shim, K.B., Lee, J.K., Song, H., 2016. The influence of FGD gypsum fabricated from limestone sludge on cement properties. J. Kor. Chem. Soc. 53 (6), 676–681.
Song, K., Jang, Y.-N., Bang, J.-H., Chae, S.-C., Kim, W., 2011a. Enhanced Cd(II) uptake by the bassanite phase contained in waste calcite produced via the carbonation of flue gas desulfurization (FGD) gypsum. Mater. Trans. 52 (6), 1303–1307.
Song, K., Kim, W., Ryu, T., Ryu, K.W., Bang, J.H., Jang, Y.N., 2011b. Adsorption of Cd(II) on waste calcite produced by the carbonation of flue gas desulfurization (FGD) gypsum. Mater. Trans. 52 (2), 224–228.
Song, W.M., Zhou, J.N., Wang, B., Li, S., Cheng, R.J., 2019. Production of SO2 gas: new and efficient utilization of flue gas desulfurization gypsum and pyrite resources. Ind. Eng. Chem. Res. 58 (44), 20450–20460.
Stout, W.L., Sharpley, A.N., Weaver, S.R., 2003. Effect of amending high phosphorus soils with flue-gas desulfurization gypsum on plant uptake and soil fractions of phosphorus. Nutrient Cycl. Agroecosyst. 67 (1), 21–29.
Sun, M.Y., Hou, J.A., Tang, T.M., Lu, R.J., Cheng, L.H., Xu, X.H., 2012. Stabilization of mercury in flue gas desulfurization gypsum from coal-fired electric power plants with additives. Fuel Process. Technol. 104, 160–166.
Tan, W.Y., Fan, W.H., Li, H.Y., Zhang, Z.X., Zhu, Y.K., 2017. Removal of Hg, as in FGD gypsum by different aqueous ammonia (amines) during CO2 sequestration. Waste Manag. Res. 35 (12), 1296–1301.
Tan, W.Y., Gu, S.P., Xia, W., Li, Y.X., Zhang, Z.X., 2018. Feature changes of mercury during the carbonation of FGD gypsum from different sources. Fuel 212, 19–26.
Tang, M.L., Li, X.R., Shen, Y.S., Shen, X.D., 2015. Kinetic model for calcium sulfate alpha-hemihydrate produced hydrothermally from gypsum formed by flue gas desulfurization. J. Appl. Crystallogr. 48, 827–835.
Tao, J., Wu, L.H., Gu, W., Zhang, H., Xu, Y.J., 2019. Effects of continuous application flue-gas desulfurization gypsum and brackish ice on soil chemical properties and maize growth in a saline soil in coastal area of China. Soil Sci. Plant Nutr. 65 (1), 82–89.
Telesca, A., Marroccoli, M., Calabrese, D., Valenti, G.L., Montagnaro, F., 2013. Flue gas desulfurization gypsum and coal fly ash as basic components of prefabricated building materials. Waste Manag. 33 (3), 628–633.
Teng, W.L., Wang, J.S., Wu, J.S., Du, Y.C., Jia, X.J., Li, H.Y., Wang, T.N., 2018. Rapid synthesis of alpha calcium sulfate hemihydrate whiskers in glycerol-water solution by using flue-gas-desulfurization gypsum solid waste. J. Cryst. Growth 496, 24–30.
Torbert, H.A., Watts, D.B., Chaney, R.L., 2018. Impact of flue gas desulfurization gypsum and manure application on transfer of potentially toxic elements to plants, soil, and runoff. J. Environ. Qual. 47 (4), 865–872.
Truman, C.C., Nuti, R.C., Truman, L.R., Dean, J.D., 2010. Feasibility of using FGD gypsum to conserve water and reduce erosion from an agricultural soil in Georgia. Catena 81 (3), 234–239.
Tzouvalas, G., Rantis, G., Tsimas, S., 2004. Alternative calcium-sulfate-bearing materials as cement retarders: Part II. FGD gypsum. Cement Concr. Res. 34 (11), 2119–2125.
Vejahati, F., Xu, Z., Gupta, R.J.F., 2010. Trace Elements in Coal: Associations with Coal and Minerals and Their Behavior during Coal Utilization – A Review.
Wang, B., Pan, Z.H., Du, Z.P., Cheng, H.G., Cheng, F.Q., 2019. Effect of impure components in flue gas desulfurization (FGD) gypsum on the generation of polymorph CaCO3 during carbonation reaction. J. Hazard. Mater. 369, 236–243.
Wang, J.M., Bai, Z.K., Yang, P.L., 2013. Effect of byproducts of flue gas desulfurization on the soluble salts composition and chemical properties of sodic soils. PloS One 8 (8), 14.
Wang, K.L., Orndorff, W., Cao, Y., Pan, W.P., 2013. Mercury transportation in soil via using gypsum from flue gas desulfurization unit in coal-fired power plant. J. Environ. Sci. 25 (9), 1858–1864.
Wang, S.J., Chen, Q., Li, Y., Zhuo, Y.Q., Xu, L.Z., 2017. Research on saline-alkali soil amelioration with FGD gypsum. Resour. Conserv. Recycl. 121, 82–92.
Wang, T., Wu, K., Wu, M., 2020. Development of green binder systems based on flue gas desulfurization gypsum and fly ash incorporating slag or steel slag powders. Construct. Build. Mater. 265, 18.
Wang, W.L., Wang, X.J., Zhu, J.P., Wang, P., Ma, C.Y., 2013. Experimental investigation and modeling of sulfoaluminate cement preparation using desulfurization gypsum and red mud. Ind. Eng. Chem. Res. 52 (3), 1261–1266.
Wang, X., Jin, B., Wang, Y.B., Xu, Z.Y., Zhang, L., Zhang, X.T., Yang, L.S., 2020. Interaction mechanism of anions in hydrothermal crystallization of desulfurization gypsum whiskers. Chem. J. Chin. Univ.-Chin. 41 (3), 473–480.
Wang, X., Jin, B., Yang, L., Zhu, X., 2015. Effect of CuCl2 on hydrothermal crystallization of calcium sulfate whiskers prepared from FGD gypsum. Cryst. Res. Technol. 50 (8), 633–640.
Wang, X., Yang, L.S., Zhu, X.F., Yang, J.K., 2014. Preparation of calcium sulfate whiskers from FGD gypsum via hydrothermal crystallization in the H2SO4-NaCl-H2O system. Particuology 17, 42–48.
Wang, Y., Wang, Z., Liang, F., Jing, X., Feng, W.J.C., 2021. Application of Flue Gas Desulfurization Gypsum Improves Multiple Functions of Saline-Sodic Soils across China, 130345.
Wansom, S., Chintasongkro, P., Srijampan, W., 2019. Water resistant blended cements containing flue-gas desulfurization gypsum, Portland cement and fly ash for structural applications. Cement Concr. Compos. 103, 134–148.
Watts, D.B., Torbert, H.A., 2017. Three annual flue gas desulfurization gypsum applications on macronutrient and micronutrient losses in runoff from bermudagrass fertilized with poultry litter. Soil Sci. 182 (1), 18–27.
Whangchai, N., Gutierrez, R., Sompong, U., Suwanpakdee, S., Pimolrat, P., Itayama, T., Ariyadet, C., Whangchai, K., 2016. Use OF flue gas desulfurization gypsum for the removal OF OFF-flavor compounds IN FISH pond water. Int. J.Geomate 11 (24), 2253–2258.
Wu, H.H., Chao, S.S., Zhou, T.H., Liu, X.B., 2018a. Cold-formed steel framing walls with infilled lightweight FGD gypsum Part I: cyclic loading tests. Thin-Walled Struct. 132, 759–770.
Wu, H.H., Chao, S.S., Zhou, T.H., Liu, Y.X., 2018b. Cold-formed steel framing walls with infilled lightweight FGD gypsum Part II: axial compression tests. Thin-Walled Struct. 132, 771–782.
Wu, Q.S., Ma, H.E., Chen, Q.J., Huang, Z.C., Zhang, C.S., Yang, T., 2019. Preparation of waterproof block by silicate clinker modified FGD gypsum. Construct. Build. Mater. 214, 318–325.
Wu, S., Wang, W.L., Ren, C.Z., Yao, X.L., Yao, Y.G., Zhang, Q.S., Li, Z.F., 2019. Calcination of calcium sulphoaluminate cement using flue gas desulfurization gypsum as whole calcium oxide source. Construct. Build. Mater. 228, 9.
Wu, X.Q., Tong, S.T., Guan, B.H., Wu, Z.B., 2011. Transformation of flue-gas-desulfurization gypsum to alpha-hemihydrated gypsum in salt solution at atmospheric pressure. Chin. J. Chem. Eng. 19 (2), 349–355.
Xie, M.Y., Li, P.P., Guo, H.F., Gao, L.X., Yu, J., 2012. Ternary system of Fe-based ionic liquid, ethanol and water for wet flue gas desulfurization. Chin. J. Chem. Eng. 20 (1), 140–145.
Xu, L.L., Wu, K., Li, N., Zhou, X.Y., Wang, P.M., 2017. Utilization of flue gas desulfurization gypsum for producing calcium sulfoaluminate cement. J. Clean. Prod. 161, 803–811.
Yan, Y.B., Dong, X.L., Sun, X.L., Sun, X.Y., Li, J.S., Shen, J.Y., Han, W.Q., Liu, X.D., Wang, L.J., 2014. Conversion of waste FGD gypsum into hydroxyapatite for removal of Pb2+ and Cd2+ from wastewater. J. Colloid Interface Sci. 429, 68–76.
Yan, Y.B., Li, Q., Sun, X.Y., Ren, Z.Y., He, F., Wang, Y.L., Wang, L.J., 2015. Recycling flue gas desulphurization (FGD) gypsum for removal of Pb(II) and Cd(II) from wastewater. J. Colloid Interface Sci. 457, 86–95.
Yang, B.J., Dong, Y.Z., Wang, B.N., Yang, M.M., Yang, C.J., 2019. A mild alcohol-salt route to synthesize alpha-hemihydrate gypsum microrods from flue gas desulfurization gypsum in large scale. Mater. Res. Express 6 (4), 13.
Yang, L., Jing, M., Lu, L.C., Zhu, X.H., Zhao, P.Q., Chen, M.X., Li, L.B., Liu, J.Y., 2020. Effects of modified materials prepared from wastes on the performance of flue gas desulfurization gypsum-based composite wall materials. Construct. Build. Mater. 257, 12.
Yang, L.C., Guan, B.H., Wu, Z.B., 2009. Characterization and precipitation mechanism of alpha-calcium sulfate hemihydrate growing out of FGD gypsum in salt solution. Sci. China Ser. E-Technol. Sci. 52 (9), 2688–2694.
Yang, P., Li, X., Tong, Z.J., Li, Q.S., He, B.Y., Wang, L.L., Guo, S.H., Xu, Z.M., 2016. Use of flue gas desulfurization gypsum for leaching Cd and Pb in reclaimed tidal flat soil. Environ. Sci. Pollut. Res. 23 (8), 7840–7848.
Yang, Z.P., Zhang, Q., Liang, L., Zhang, X.Z., Wang, Y.L., Guo, C.X., Guo, J.L., 2018. Remediation of heavily saline-sodic soil with flue gas desulfurization gypsum in Arid-Inland China. Soil Sci. Plant Nutr. 64 (4), 526–534.
Ye, J., Zubair, M., Wang, S., Cai, Y., Zhang, P.J.W.E.R., 2019. Power Production Waste 91, 1091–1096.
Yu, D.X., Zhou, J., Shu, Z., Wang, Y.X., 2016. High-strength, cement-free concrete of flue gas desulfurization gypsum-based non-fired brick. ACI Mater. J. 113 (6), 745–752.
Yu, H.L., Yang, P.L., Lin, H., Ren, S.M., He, X., 2014. Effects of sodic soil reclamation using flue gas desulphurization gypsum on soil pore characteristics, bulk density, and saturated hydraulic conductivity. Soil Sci. Soc. Am. J. 78 (4), 1201–1213.
Zhai, W.W., Dai, Y.X., Zhao, W.L., Yuan, H.H., Qiu, D.S., Chen, J.P., Gustave, W., Maguffin, S.C., Chen, Z., Liu, X.M., Tang, X.J., Xu, J.M., 2020. Simultaneous immobilization of the cadmium, lead and arsenic in paddy soils amended with titanium gypsum. Environ. Pollut. 258, 10.
Zhang, X.F., Wang, J.S., Wu, J.S., Jia, X.J., Du, Y.C., Li, H.Y., Zhao, B.X., 2016. Phase- and morphology-controlled crystallization of gypsum by using flue-gas-desulfurization gypsum solid waste. J. Alloys Compd. 674, 200–206.
Zhang, Y.J., Pan, F., Wu, R., 2016. Study on the performance of FGD gypsum-metakaolin-cement composite cementitious system. Construct. Build. Mater. 128, 1–11.
Zhao, F.Q., Liu, H.J., Hao, L.X., Li, Q., 2012. Water resistant block from desulfurization gypsum. Construct. Build. Mater. 27 (1), 531–533.
Zhao, S.L., Duan, Y.F., Lu, J.C., Gupta, R., Pudasainee, D., Liu, S., Liu, M., Lu, J.H., 2018. Thermal stability, chemical speciation and leaching characteristics of hazardous trace elements in FGD gypsum from coal-fired power plants. Fuel 231 (NOV.1), 94–100.
Zhao, S.L., Duan, Y.F., Chen, L., Li, Y.N., Yao, T., Liu, S., Liu, M., Lu, J.H., 2017. Study on emission of hazardous trace elements in a 350 MW coal-fired power plant. Part 2. arsenic, chromium, barium, manganese, lead. Environ. Pollut. 226, 404–411.
Zhao, Y.G., Wang, S.J., Li, Y., Liu, J., Zhuo, Y.Q., Chen, H.X., Wang, J., Xu, L.Z., Sun, Z.T., 2018a. Extensive reclamation of saline-sodic soils with flue gas desulfurization gypsum on the Songnen Plain, Northeast China. Geoderma 321, 52–60.
Zhao, Y.G., Wang, S.J., Li, Y., Liu, J., Zhuo, Y.Q., Zhang, W.K., Wang, J., Xu, L.Z., 2018b. Long-term performance of flue gas desulfurization gypsum in a large-scale application in a saline-alkali wasteland in northwest China. Agric. Ecosyst. Environ. 261, 115–124.
Zhao, Y.G., Wang, S.J., Li, Y., Zhuo, Y.Q., Liu, J., 2019a. Effects of straw layer and flue gas desulfurization gypsum treatments on soil salinity and sodicity in relation to sunflower yield. Geoderma 352, 13–21.
Zhao, Y.G., Wang, S.J., Li, Y., Zhuo, Y.Q., Liu, J., 2019b. Sustainable effects of gypsum from desulphurization of flue gas on the reclamation of sodic soil after 17 years. Eur. J. Soil Sci. 70 (5), 1082–1097.
Zhao, Y.G., Zhang, W.C., Wang, S.J., Liu, J., Li, Y., Zhuo, Y.Q., 2020. Effects of soil moisture on the reclamation of sodic soil by flue gas desulfurization gypsum. Geoderma 375, 10.

Zheng, D., Lu, H.L., Sun, X.Y., Liu, X.D., Han, W.Q., Wang, L.J., 2013. Reaction mechanism of reductive decomposition of FGD gypsum with anthracite. Thermochim. Acta 559, 23–31.
Zhong, S.Y., Ni, K., Li, J.M., 2012. Properties of mortars made by uncalcined FGD gypsum-fly ash-ground granulated blast furnace slag composite binder. Waste Manag. 32 (7), 1468–1472.
Zhong, Y., Gao, J., Chen, P., Guo, Z., 2017. Recovery of potassium from K-feldspar by thermal decomposition with flue gas desulfurization gypsum and CaCO3: analysis of mechanism and kinetics. Energy Fuels 31 (1), 699–707.
Zhu, Z.W., Zhuo, Y.Q., Fan, Y.M., Wang, Z.P., 2017. Mechanism of mercury vapor release from flue gas desulfurization gypsum. Fuel Process. Technol. 156, 485–490.
Zou, R.J., Zeng, X.B., Luo, G.Q., Qiu, Y., Zhang, B., Xu, Y., Wu, H., Yao, H., 2016. Mercury stability of byproducts from wet flue gas desulfurization devices. Fuel 186, 215–221.